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Tornadoes: Their Structure, Genesis Mechanism and Environment

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1. Introduction

Tornadoes are small-scale atmospheric vortices that are accompanied by the strongest near-surface wind among various atmospheric disturbances. Since violent tornadoes can cause serious damage to lives and structures, efforts to clarify their structure, genesis mechanism and environment have been extensively made. However, their small spatial scale and short lifetime prevent us from their satisfactory clarification. The present paper attempts to summarize our current understanding of their structure, genesis mechanism and environment.

2. Hierarchy of atmospheric disturbances that cause tornadoes

Currently it is considered that there are two representative situations in which tornadoes are formed. One is associated with a meso-scale front and the other with a supercell, which is a special type of cumulonimbus cloud. Since most of the strong and violent tornadoes occur in the latter situation, however, we will be hereafter confined to tornadoes caused by a supercell.

A supercell develops in an environment with strong vertical shear and relatively unstable vertical stratification. It is characterized by a rotating updraft called a mesocyclone (MC), which has a diameter on the order of several kilometer, and vertical vorticity exceeding $10^{-2}s^{-1}$. Two kinds of MCs exists: mid-level and low-level MCs. The mid-level MC is formed by tilting horizontal vorticity associated with the vertical shear of the environmental wind by the storm updraft, while the low-level MC by tilting baroclinically-generated horizontal vorticity due to horizontal temperature gradient at the periphery of a rain-cooled downdraft. A statistics of Doppler radar observations in the United States, however, shows that only 15% (40%) of mid-level (low-level) MCs are associated with tornadoes. Thus, some near-surface processes in the storm are likely to play an important role in a tornadogenesis.

It is considered that a supercell tornado is generated by tilting near-surface horizontal vorticity by the strong updraft associated with the low-level MC. Three possible sources for such horizontal vorticity have been suggested, but which is most important has not clarified yet (this problem will be considered again in section 4).

A considerable fraction of tornadoes are associated with extratropical and tropical cyclones. Extratropical cyclones (ECs) that cause more than 15 tornadoes (OCs) in the United States have larger convective available potential energy (CAPE), which gives a measure of storm updrafts, and larger storm-relative environmental helicity (SREH), which gives a measure of tendency to have a mesocyclone, than ECs that cause less than 5 tornadoes (NOCs)[1,2]. Furthermore, the westerly jet in the environment of OCs is found to have a stronger anticyclonic shear than that of NOCs.

Tornado-spawning typhoons also have larger CAPE and SREH than those for typhoons that do not spawn tornadoes. Especially the northeast quadrant of typhoons where tornadoes occur frequently has large SREH and entraining CAPE, which consider the effect of entrainment of the environmental air[3]. Thus, the environment of cyclones determines the structure of the cyclones, which provide environment favorable for supercells, which in turn spawn tornadoes.

3. Structure of tornado vortices

Tornado vortices have various morphology: a thin laminar vortex, a thick turbulent vortex, a helical vortex and a vortex having subsidiary vortices (multiple-vortex). Theoretical and laboratory studies suggest that their morphology is mainly determined by a non-dimensional parameter called “swirl ratio”. Tornadoes in the real atmosphere moves at a certain speed, and detailed structure of a translating tornado vortex is not well understood. Recently high-resolution numerical simulation succeeded in reproducing an observed multiple-vortex tornado and revealed some of its detailed structure[4].

4. Mechanism of a tornadogenesis

Recently, ensemble simulations of Tsukuba F3 tornado on 6 May 2012 in Ibaraki prefecture, Japan were made[5]. The circulation budget analysis for backward trajectories of particles placed in the simulated tornado shows that, among the three possible sources for the horizontal vorticity (see section 2), frictionally-generated horizontal vorticity is the largest contributor to the rotation of the tornado. However, the results of the ensemble sensitivity analysis shows that the strength of the simulated tornadoes has little correlation with the way the horizontal vorticity is generated, but rather has strong correlation with the strength of the low-level MC and near-surface relative humidity both of which contribute to strengthen the low-level updraft.

This result seems to encourage a future tornado prediction based on a numerical model having a horizontal grid size of 300-m, which resolves a low-level MC but not a tornado directly.

References

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